JUNE 12, 2020

CAV TASK 1.2: TRAFFIC MICRO-SIMULATION OF ENERGY IMPACTS OF CONNECTED AND AUTOMATED VEHICLES (CAV) CONCEPTS AT VARIOUS MARKET PENETRATIONS

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OVERVIEW: TIMELINE, BUDGET, BARRIERS & PARTNERS

- Timeline
  - Project start date: Jan 1 2017
  - Project end date: Sept 30 2019
  - Percent complete: 100%
- Budget
  - Total project funding: $681K
    - 100% DOE/VTO
  - Funding for FY 2017: $181K
  - Funding for FY 2018: $250K
  - Funding for FY 2019: $250K
- Collaboration
  - Berkeley Lab (project lead)
  - UC Berkeley
  - Output: used by EEMS075: Micro to Meso
- Barriers
  - See next slide

OVERVIEW: BARRIERS

- Rapid evolution of vehicle technologies and services enabled by connectivity and automation
  - Advanced intersection management using Connected Automated Vehicle (CAV) technologies
  - Require new signal control algorithms for maximizing **intersection mobility** based on **CAV information**
  - Potential of developing a **centralized vehicle trajectory control** for improving vehicle **energy efficiency**
  - **Active traffic management (ATM)** strategies available for improving the freeway traffic flow
- Determining the value and productivity derived from new mobility technologies
  - Need to quantify the **energy benefit** of the new intersection control strategy and ATMs
  - Address the uncertainty of the system performance under **partial CAV environment**

RELEVANCE AND OBJECTIVES

- Relevance
  - Vehicle energy savings are affected by factors at **meso/macroscopic traffic flow** level, **local vehicle following** level, and **vehicle dynamics** level
  - Progressively increasing **market penetration of CAVs** and **ATM** changes the traffic flow patterns significantly
  - Field test of CAV impact on energy savings in traffic level is very expensive, not fitting for first-step tests
- Objectives
  - Developing an ATM that maximizes the **intersection mobility** and improves the **vehicle energy efficiency** at the same time via **CAV capabilities**
  - Adopt ATMs for improved freeway performances
  - Simulating **energy saving benefit** of the ATM at typical four-leg intersections
  - Evaluating the system performance under different **CAV market penetrations**

MILESTONES

Milestone	Milestone or Deliverable Description	Milestone Type / Go/No-Go Criteria	Status
Q1	Initial network model with freeway and arterial	Operation level micro-traffic simulation model in Aimsun	Completed
Q2	Calibrated network traffic with CACC model	Operation level micro-traffic simulation model in Aimsun	Completed
Q3	Implemented ATM for both freeway and arterial with optimal coordination	Operation level micro-traffic simulation model in Aimsun	Completed
Q4	Data from extensive simulation with analysis results	Report on energy saving benefit for CACC operation over network traffic with ATM and coordination strategies	Completed

APPROACH

- Cooperative signal control algorithm with and without trajectory planning
- Modeling freeway mobility and energy performance under various advanced traffic management strategies

APPROACH

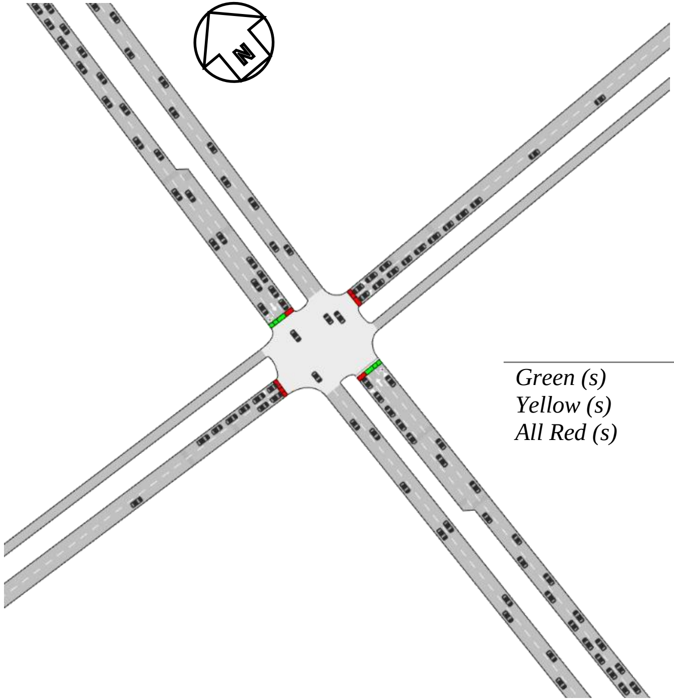
Signal control algorithm

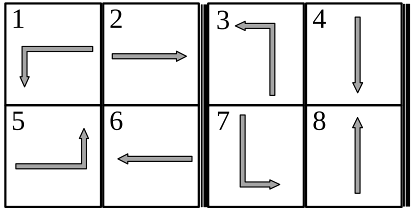
- Identify the optimal signal phase sequence, signal timing and number of stages
  - **Maximize the overall intersection throughout** over a control horizon
  - Use **real-time CAV information** for accurate traffic status perception and prediction
  - **Flexible cycle length**, adaptive to demand variations
  - **Simple algorithm**, relies on predictions of two vehicle states: pass without slow down and pass after joining the queue
- Incorporate trajectory planning
  - Guide the subject vehicle to pass the intersection **without full stop**
  - Reduce energy loss by **eliminating stops in queue**
  - Increase intersection throughput by **increasing vehicle speed** when they pass the stop bar

See technical backup slides 27-34 for methodology details

ACCOMPLISHMENTS

Algorithm test at a simulated intersection





	EB/WB Left	EB/WB Through	NB/SB Left	NB/SB Through
Green (s)	8	14	6	46
Yellow (s)	3	3	3	3
All Red (s)	2	2	2	2

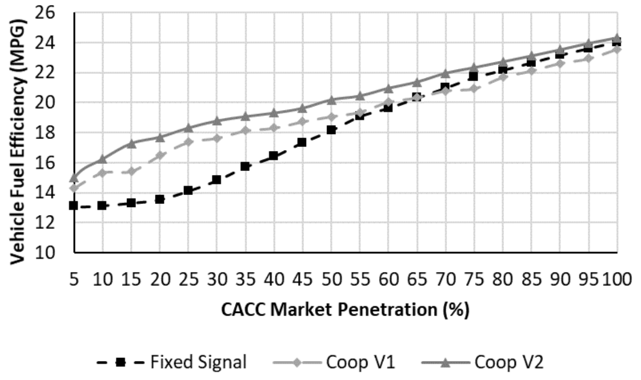
Liu, H., Lu, X. Y., & Shladover, S. E. (2019). Traffic signal control by leveraging Cooperative Adaptive Cruise Control (CACC) vehicle platooning capabilities. *Transportation research part C: emerging technologies*, *104*, 390-407.

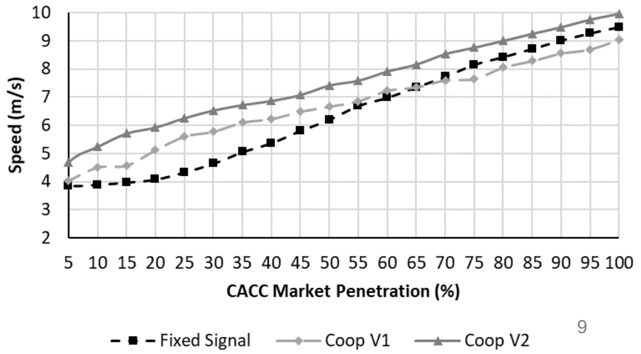
- **Baseline case: fixed signal control (signal timings in the figure)**
- **V1 case: our previous signal control algorithm without trajectory planning (Liu et a., 2019)**
- **V2 case: the proposed signal control algorithm with/without trajectory planning**
- **Traffic inputs: major road—1780 veh/hr, minor road—430 veh/hr, saturated flow at the baseline case**
- **Vehicle energy consumption estimated using the MOVES model**

ACCOMPLISHMENTS

Results (trajectory planning turned off for the V2 case)

- The signal optimization algorithm saves energy:
  - Many vehicles can pass the intersection without joining the queue – fewer deceleration
  - The queue vehicles can pass the intersection without waiting for multiple cycles – less idling time
- The benefits become smaller at higher CACC market penetrations
  - The increased CACC string operations lead to significant reduction of queues
  - The baseline signal can serve the queued vehicles already
- V2 is significantly better than V1

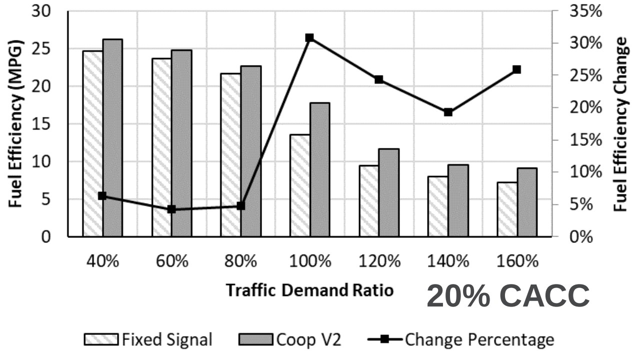




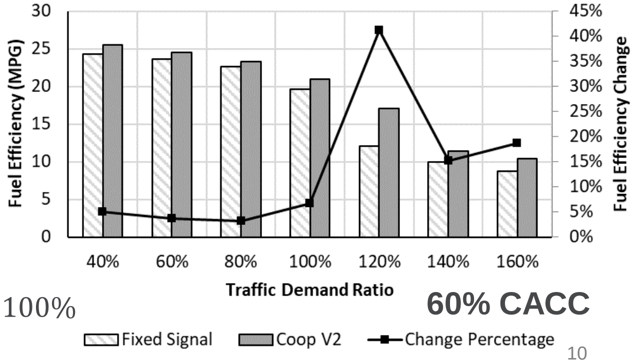
ACCOMPLISHMENTS

Results (trajectory planning turned off for the V2 case)

- **The proposed signal control algorithm generates the most significant benefits when the intersection is saturated**
  - **As the demand increases, the intersection traffic becomes saturated**
  - **Around 5% fuel efficiency improvement in under-saturated cases regardless of the CACC market penetration**
  - **30%-40% fuel efficiency increase in saturated cases—the proposed algorithm reduced the number of queued vehicles and vehicles that wait for multiple cycles before passing the intersection under the saturated condition**
  - **15%-25% fuel efficiency increase in oversaturated cases—long queues exceed the capability the signal control algorithm can handle in the control horizon**



20% CACC



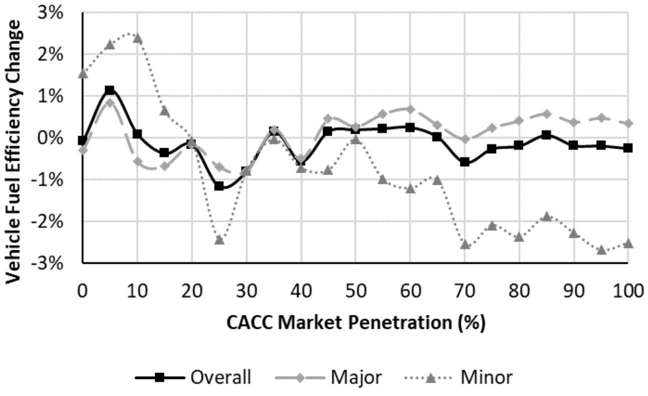
60% CACC

$$Traffic\ demand\ ratio = \frac{Input\ demand}{Saturated\ demand\ of\ the\ 0\%\ CACC\ case} \times 100\%$$

ACCOMPLISHMENTS

Performance of V2 when the trajectory planning is turned on

- **The overall benefit of trajectory planning is small**
- **The algorithm is deactivated frequently due to cut-ins**
- **There are uncertainties in predicting when the queue starts to move, especially if the queue contains mixed traffic**
- **It makes the subject vehicle stop when it joins the queue but the queue has not yet started moving**
- **This removes the energy benefit**



The fuel efficiency change was measured against the V2 non-trajectory planning case with the demand ratio of 100%.

More detailed analysis can be found in slides 33-35

APPROACH

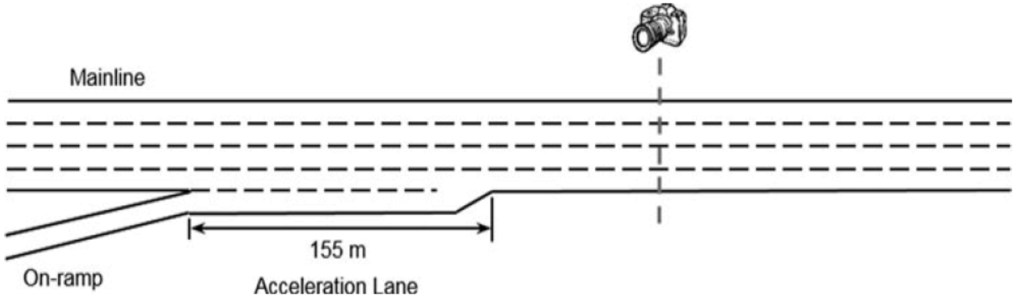
Modeling freeway mobility and energy performance under ATM

- **Case 1: Isolated Freeway Merge Bottleneck**
  – Determine the ramp metering rate to maintain the maximum mainline capacity
  – Quantify the environmental effects of ramp metering via Autonomie
  – Explore traffic mobility performance under the ramp metering control
- **Case 2: Real-World Freeway Corridor (CA SR-99)**
  – Apply Local responsive ramp metering (LRRM), Coordinated ramp metering (CRM), and Variable speed advisory (VSA)
    - **LRRM**: determine RM rates based on traffic conditions of isolated bottlenecks
    - **CRM:** determine RM rates by looking at the occupancy/flow of the whole corridor
    - **VSA:** regulate the speed of freeway sections upstream from bottlenecks for maintaining the capacity flow at bottlenecks
  – Investigate and compare the mobility, fuel consumption and emission performance

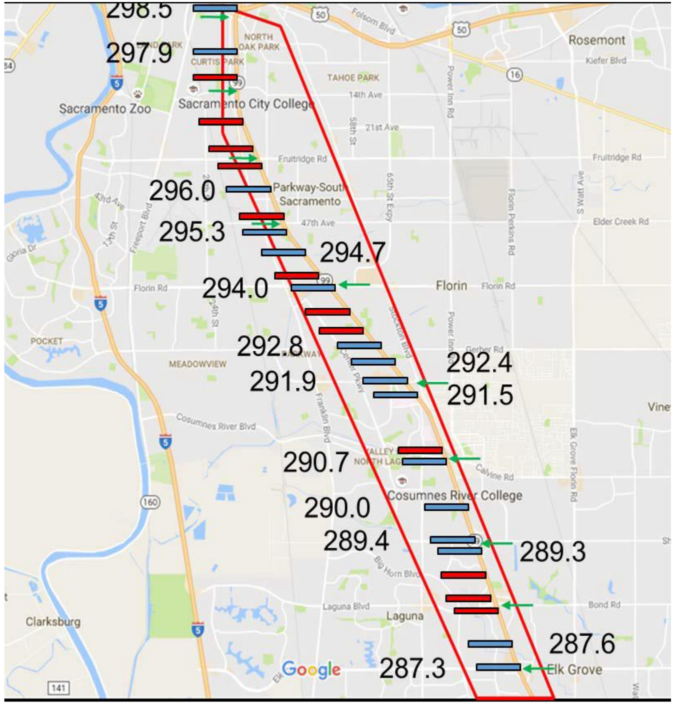
See technical backup slides 36-39 for methodology details

ACCOMPLISHMENTS

Freeway evaluation under various advanced traffic management strategies



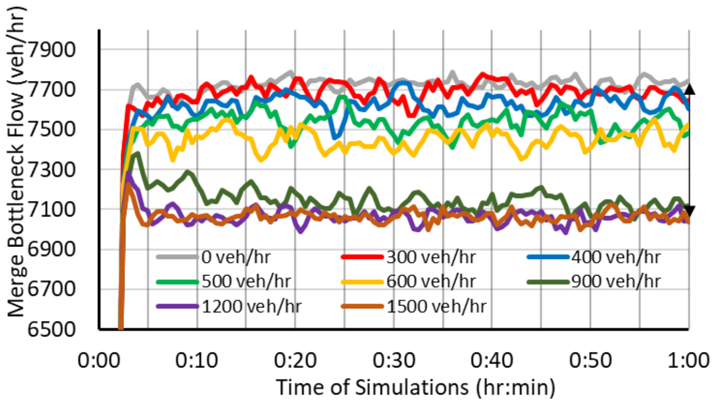
- Isolated on-ramp bottleneck
- Freeway corridor

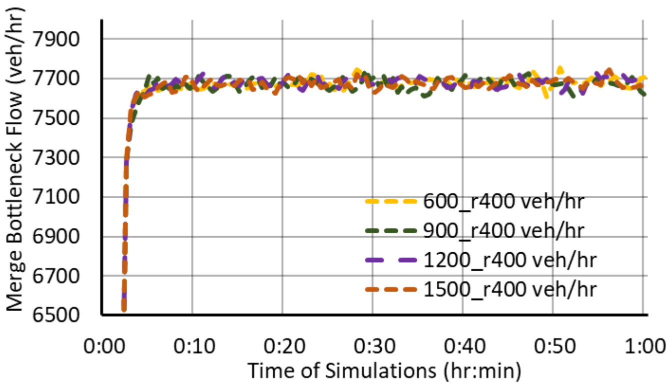


ACCOMPLISHMENTS

Performance of isolated bottleneck

- LRRM used for identifying the benefit of the widely applied controller
- Capacity drop without LRRM (upper plot)
  - Capacity drop at 400 veh/hr on-ramp demand;
  - Maximum reduction at 900 veh/hr;
  - The capacity reduction is about 9%.
- No capacity drop with LRRM (lower plot)
  - RM rate of 400 veh/hr to prevent capacity drop;
  - Capacity recovers to its original level;
  - Traffic mobility performance improves.





ACCOMPLISHMENTS

Performance of freeway corridor

Ramp metering strategy	No metering	LRRM	CRM & VSA	CRM	VSA
Delay (sec/km)	31.69	-9%	-45%	-47%	-45%
Average speed (km/hr)	65.53	2%	13%	14%	12%
Number of lane changes (#/km)	1709.19	-1%	-13%	-13%	-13%
Fuel Economy (MPG)	31.39	1%	28%	28%	27%
NOx (kg/veh/mile)	1.95E-04	-2%	-22%	-24%	-22%
CO (kg/veh/mile)	1.96E-03	-2%	-22%	-23%	-21%
CO2 (kg/veh/mile)	0.291	-1%	-22%	-22%	-22%
HC (kg/veh/mile)	3.63E-04	-2%	-22%	-23%	-21%
PM 2.5 (kg/veh/mile)	1.37E-05	-1%	-22%	-22%	-21%

- Various ATM strategies used for achieving a comprehensive understanding of the corridor performance
- LRRM provided 2-9% mobility and 1-2% emission and fuel consumption improvements, compared to the no metering case;
- CRM and VSA both achieved over 20% improvements in mobility, emissions and fuel consumptions;
- CRM worked slightly better than VSA alone.

More detailed analysis can be found in slides 40-41

RESPONSES TO PREVIOUS YEARS REVIEWERS COMMENTS

- The use of the Motor Vehicle Emission Simulator (MOVES) model for fuel consumption estimation may not provide accurate results, especially in the case of CACC. The reviewer asked whether the project team adjusted fuel consumption rates from MOVES for the aerodynamic effect on fuel consumption of the following vehicles in CACC strings.
  - We agree with the reviewer. Incorporating aerodynamic effect on the fuel estimation is an on-going research effort of the research team. Previously, we have integrated the aerodynamic component into the MOVES truck energy consumption model. We are developing a similar approach for the passenger cars. But the passenger car model was not ready when we analyzed the CACC traffic last year. We hope to update the results in our upcoming analyses.
- Without any clear explanations of why these trends are occurring, the reviewer said it can be difficult to suggest future actions.
  - Thanks for the comments. We explained the traffic flow factors that contributed the capacity and energy trends. The vehicle dynamics factors have not been identified due to the lack of detailed vehicle operation data. This would be a very interesting topic to analysis in the upcoming studies.
- There should also be more description of the powertrain(s) used.
  - We agree with the reviewer. Our current analysis only considered traditional ICE passenger cars. With more datasets from vehicles with different types of powertrains, we should be able to develop models for those vehicles and perform further analyses on their effects.

RESPONSES TO PREVIOUS YEARS REVIEWERS COMMENTS

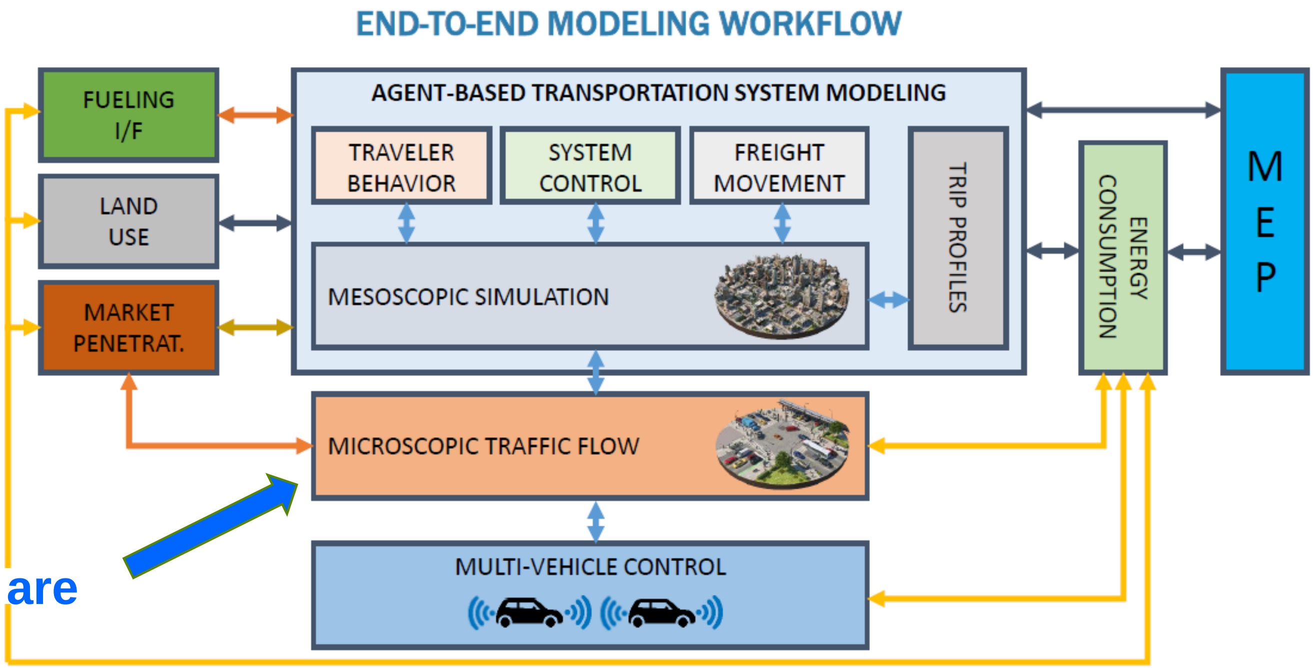
- The reviewer stated that it would also be good to add some stochastic nature to the modeling since human behavior is involved.
  - Our human driver car-following and lane-changing models did include random functions to model the stochastic nature of the driver behavior. Particularly, we have adopted stochastic desired speed, desired headway, reaction time, lane-changing motivation, and the acceptable gap for lane changes. Those parameters cover major aspects involved in a driver’s driving tasks.
- The reviewer asked what the level of traffic congestion is in the simulation.
  - Our traffic simulation reproduces the freeway bottlenecks with the existing traffic flow inputs during typical morning peak hours. The sensitivity analysis regarding the congestion level has been conducted in a later project. The results will be released in a forthcoming TRR paper.
- The project team could benefit from collaboration with vehicle fuel consumption modeling experts.
  - Thanks. We have been collaborating with the Argonne team to learn their methodologies on the vehicle energy consumption modeling. Particularly, we are implementing the Autonomie model with our simulation data for the energy estimation. The estimation results should be out in the coming year.

RESPONSES TO PREVIOUS YEARS REVIEWERS COMMENTS

- The reviewer noted that there is no collaboration outside of the SMART Mobility. The reviewer stated that it would have been beneficial to have a least one other entity (National Laboratory, industry, or governmental) actively involved to provide additional perspective and validation.
  – We do have cooperation with ANL and ORNL, but funds were independent.
- The reviewer stated that it may be better to stay largely focused on the V2V elements of CACC and management strategies through further validation and optimization of the results.
  – The successful implementation of advanced traffic management strategies requires closely collaboration of the road users and infrastructure. Many strategies such as ramp metering and speed harmonization do need coordination offered by a centralized controller. In this case, the V2I and I2V elements also need to be considered.
- The reviewer remarked that the level of funding seems a bit excessive for such a traffic micro-simulation project.
  – The project includes extensive simulation model development, test, and evaluation of the modeling behaviors under different road networks and traffic conditions. The funding is sufficient for the comprehensive study.

COLLABORATION AND COORDINATION WITH OTHER INSTITUTIONS

Where it Fits in Workflow



Where we are

COLLABORATION AND COORDINATION WITH OTHER INSTITUTIONS

- Berkeley Lab (project lead)
- UC Berkeley: Researchers and Post-docs
- ANL
- ORNL

REMAINING CHALLENGES AND BARRIERS

- Errors in estimating the departure set for the signal optimization
  - A simple kinematic model is not accurate enough for estimating the vehicle travel distance
  - Uncertainty in estimating the reaction delay of human drivers and CACC controllers in the queue discharging process
- The current trajectory planning algorithm does not provide significant energy improvement under mixed traffic
  - When the preceding queue contains human drivers, there is uncertainty in predicting human driver behaviors
  - Only active under limited cases
- CRM and VSA reduce total vehicle miles traveled, which is unexpected.
- MOVES model might not be able to capture vehicle acceleration/deceleration behaviors with high resolution
  - Errors of energy estimation at intersections where vehicles frequently accelerate and decelerate

PROPOSED FUTURE RESEARCH

- Improve the signal control algorithm for better predicting the human driver behaviors
- Extend the algorithm for arterial corridors
- Develop improved trajectory planning algorithm for application under mixed traffic flow
- Simulate fuel saving benefit for CACC vehicle operation along an arterial corridor with Active Traffic Signal Control (ATSC)
- Further investigate the impacts of CRM and VSA on the freeway corridor performance.
- Build a more accurate fuel consumption estimation model for arterial intersection operations in microscopic simulation
- Any proposed future work is subject to change based on funding levels.

SUMMARY

- The signal optimization algorithm improves average vehicle energy efficiency by 1% to 30%
- The highest improvement was observed when the CACC market penetration is between 15% to 30%
- As CACC market penetration increases, the benefit of the signal algorithm becomes smaller because the increased CACC string operation improves traffic flow, making the benefit of the signal controller less significant
- Regardless the CACC market penetration, the signal controller performs the best in the saturated conditions (i.e., the demand reached the capacity)
- The trajectory planning algorithm provides little additional benefit because it has limited effects in mixed traffic
- The ramp metering strategy increases the mobility and energy performance for both the isolated freeway bottleneck and corridor
- The VSA strategy benefits the mobility and vehicle energy efficiency of the freeway corridor

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FOR MORE INFORMATION

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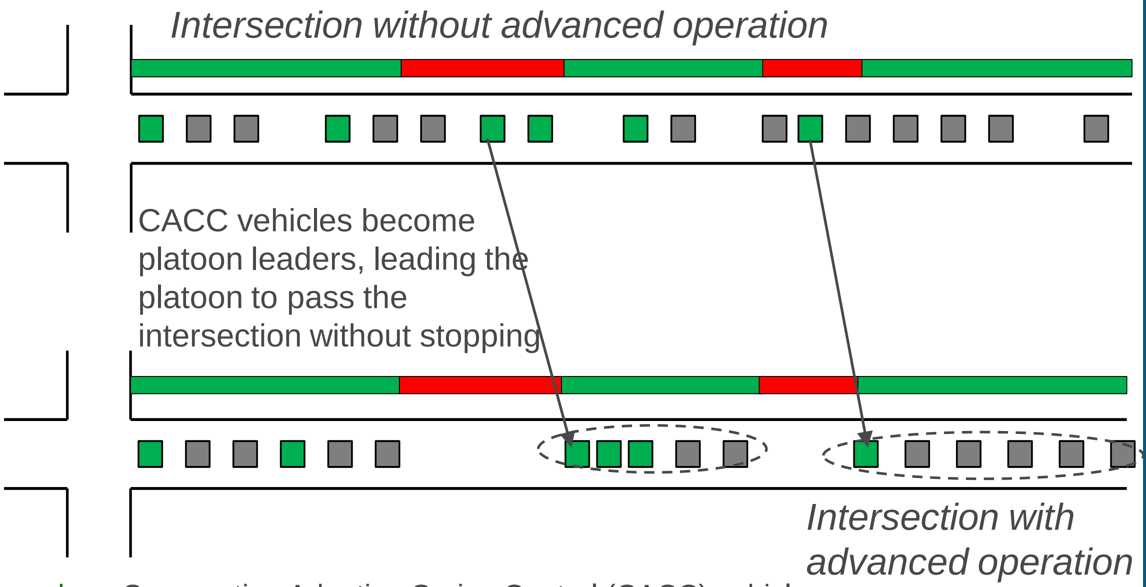
TECHNICAL BACKUP SLIDES

APPROACH

An intuitive idea on intersection operation



Green box: Cooperative Adaptive Cruise Control (CACC) vehicle
Gray box: manually driven vehicle
Platoon: a group of vehicles that can pass the intersection during the same green phase

Existing intersection operation:

- **Vehicles arrive randomly at the intersection**
- **Some can pass during the green phase**
- **Others need to stop on red signal**

Advanced Intersection Operation

- **An advanced signal control algorithm that predicts arrival patterns based on CACC vehicle information**
- **Optimize phase sequence and times to maximize throughput**
- **Platoon leaders adopt trajectory planning to avoid stopping during red**

APPROACH

Proposed signal control algorithm with trajectory planning

- **Flexible cycle length**, adaptive to demand variations
- **Simple algorithm**, relies on predictions of two vehicle states: pass without slow down and pass after joining the queue
- **Fast search for optimal solutions**: using parallel computing with dynamic programming and taking advantage of the monotonic value function
- Incorporate **trajectory planning** with signal optimization
- Feasible for **mixed traffic conditions**

APPROACH

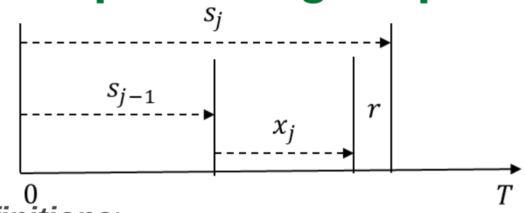
Signal control algorithm—a dynamic programming method

- Objective: maximize throughput
- Throughput: $Q_j = \sum_{i=1}^{N} D_j$
  - where j is stage (phase) ID; i is the number of intersection approaches; D_j is the number of departure vehicles
- Performance function (total throughput of the current stage and previous stages): $v_j = v_{j-1} + Q_j$
- Identify the optimal signal phase sequence, signal timing and number of stages that **maximizes the performance function** over a control horizon
- The cycle length varies based on the optimal signal timing and stage numbers

APPROACH

A dynamic programming approach for searching the optimal signal plan

- Forward recursion:
  - Step 1: initialize $v_0 = 0,\, j = 1$
  - Step 2: for $s_j = r, \ldots, T$, compute $v_j(s_j) = \max_{x_j}\{v_{j-1}(s_{j-1}) + Q_j(s_j, x_j)\}$
  - Step 3: if $j < P$, $j = j + 1$ and go to Step 1; else if $v_{j-k}(T) = v_j(T)\ \forall k \leq P - 1$, STOP; else $j = j + 1$ and go to Step 1.
- Backward retrieval:
  - Step 1: $s_{J-(P-1)} = T$
  - Step 2: for $j = J - (P-1), \ldots, 1$, read $x_j^*(s_j^*)$ from the results computed by forward recursion
  - Step 3: if $j > 1$, $s_{j-1}^* = s_j^* - (x_j^* + r) \cdot \sigma_{x_j^*}$



Definitions:

- j: stage ID, each stage corresponds to a phase
- r: all red time, e.g., 2 s
- T: control horizon, e.g., 90 s
- P: total number of phases, e.g., 4
- s: state variable, total time allocated to a stage
- x: control variable, e.g., green time allocated to a stage
- J: last stage ID
- $x_j^*(s_j^*)$: optimal green time computed at each stage
- $\sigma_{x_j^*}$: indicator function, $\sigma_{x_j^*} = 1$ if $x_j^* > 0$, $\sigma_{x_j^*} = 0$ otherwise

APPROACH

Computation of vehicle departure D_j for estimating the throughput

- Based on the traffic information collected from CAVs
  - Real-time location and speed of CAVs are directly obtained
  - Location and speed of manually driven vehicles are estimated based on the CAV information
- The computation of D_j is performed for different potential signal timings until the optimal timing is identified
- Vehicle departure depends on the future vehicles trajectories
  - Simple kinematic models for the leader of a platoon
  - Consider different car-following behaviors of manually driven vehicles and CAVs
  - Different desired gap and reaction time for manually driven vehicles and CAVs

APPROACH

Computation of vehicle departure D_j for a given s_j and x_j

- Step 1: Determine if a subject vehicle will join the queue before green starts
- Step 2:
  - If yes, the vehicle will stop in queue. Compute travel distance d_s within green time x_j
  - If no, the vehicle will pass the intersection without deceleration. Compute the travel distance d_f within stage time s_j
- Step 3:
  - If $d_s > queue\ length$, count the subject vehicle in the departure set
  - Else If $d_s > intersection\ length$, count the subject vehicle in the departure set
- Step 4: repeat Step 1-3 for all vehicles within the intersection area

APPROACH

Vehicle trajectory planning

- Guide the subject vehicle to pass the intersection without full stop
  - Cruise at a low speed during red
  - Join the end of the queue just as the signal turns green
- Reduce energy loss by **eliminating stops in queue**
- Increase intersection throughput by **increasing vehicle speed** when they pass the stop bar
- Only applies to the platoon leaders
  - Algorithm deactivates when the planned speed is higher than the car-following speed given by the on-board controller (safety consideration)
  - Algorithm deactivates when the queue length changes (cut-in handling)

APPROACH

Vehicle trajectory planning—a simple controller

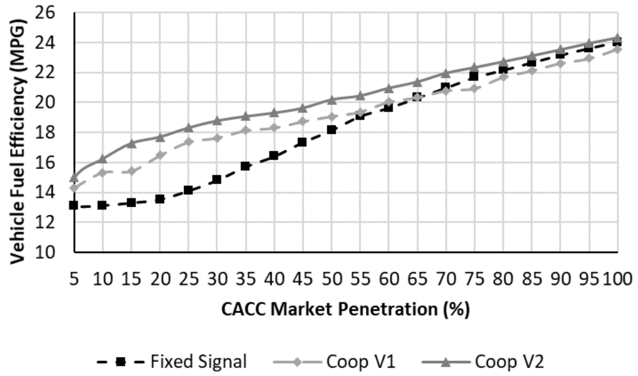
$$a = k_t \cdot (t_{est} - t_{re})$$

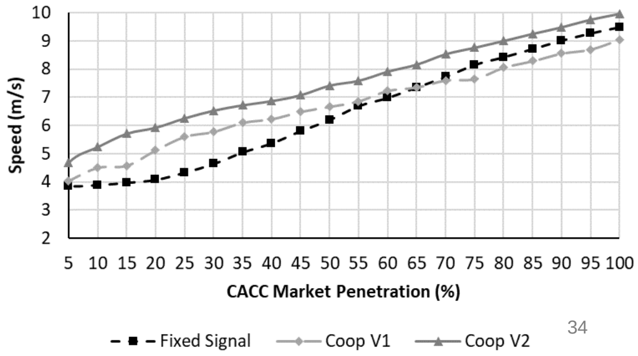
– $a_{min} \leq a \leq a_{max}$, k_t is the control gain
– $t_{est} = {}^{d}/_{v_t}$, estimated time to arrival, d is the distance to the stop bar or to the end of the queue (plus an equilibrium distance), v_t is the current speed
– t_{re} is the remaining time before the green, obtained from the signal optimization algorithm

ACCOMPLISHMENTS

Results (trajectory planning turned off for the V2 case)

- Evaluate the benefit obtained from the signal control optimization only
- Both cooperative algorithms outperform the baseline case at low and median CACC market penetrations
- The benefits become smaller at higher CACC market penetrations

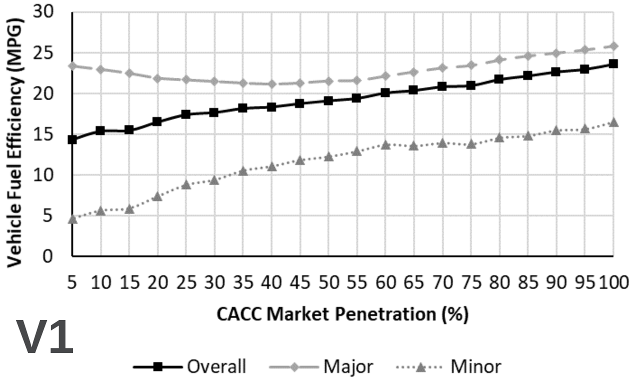




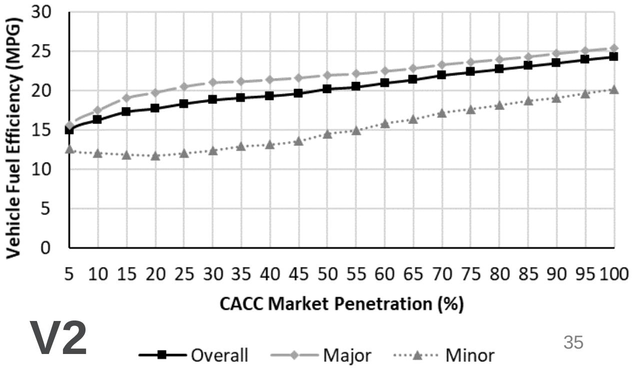
ACCOMPLISHMENTS

Results (trajectory planning turned off for the V2 case)

- Comparing the effects of the two algorithms on the major and minor road separately
- V1 overly penalizes the minor approach to achieve the overall performance optimization
- V2 generates balanced performance
- V2 is better than V1 because it adopts a variable cycle length
  - The cycle length of V2 changes based on the varying traffic demand input, resulting more suitable signal plans for traffic flow dynamics
  - The variable cycle length allows V2 to give just enough green time to both the major and minor approach, avoiding green time waste



V1

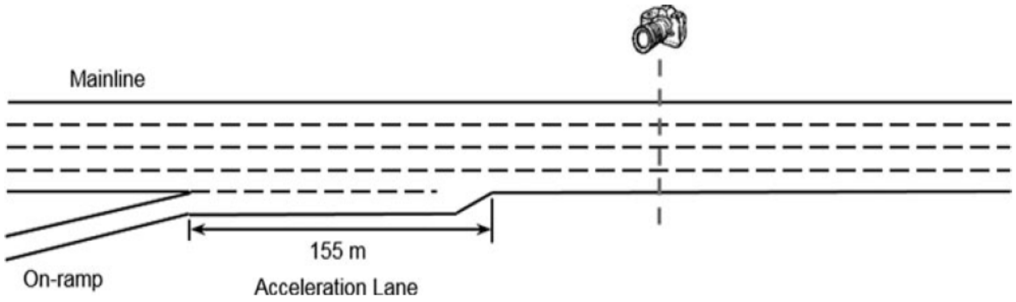


V2

APPROACH

Isolated Merge Bottleneck

- One-hour simulation, 10 replications for each scenario
- Mainline flow: 8,000 vph
- On-ramp demand: 0-1,500 vph, 300 increments
- Ramp metering algorithm: fixed metering rate, which can maintain the maximum mainline throughput
- External behavior model:
  - Reaction time: 1.2 s
  - Mean headway: 1.4 m
  - Maximum acceleration: 1.5 m/s2
  - Maximum deceleration: -4.0 m/s2
  - Lane-changing desire threshold: 0.4



APPROACH

Implementation of Autonomie

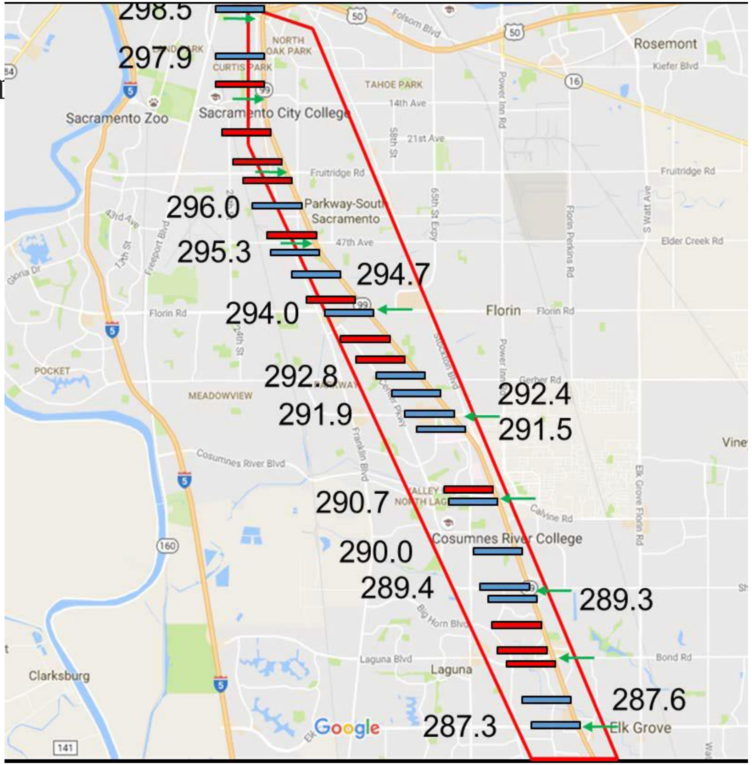
- The steps of Autonomie’s energy evaluation are shown below:

- Step 1: Export the trajectory SQLite files generated in Aimsun to .csv files to run (using 10% trajectory data for energy evaluation can maintain reasonable accuracy while significantly reduce computation time);
- Step 2: Setup parameters, which includes: Aimsun trajectory filename, Scenario file: ANL provided xml file defining the scenarios and vehicle mapping, Vehicle class: ‘LD’ for light-duty and ‘HD’ for medium-duty/heavy-duty, and Output results filename: Energy results database filename (.csv);
- Step 3: Obtain the results database: the results is in .csv format, each row corresponds to the results of a single trip in the trajectory database, and the information (columns) includes Vehicle ID / Vehicle filename, Fuel consumption (kg), Fuel consumption per mile (kg/mile), Electrical consumption (J), Driving distance (miles), Fuel economy (mpg), Emissions – GHGS, VOC, CO, PM10, PM2p5, NOx, SOx, BC, POC, CH4, N2O (kg/km).

APPROACH

Freeway Corridor Simulation

- SR-99 freeway corridor, 16 on-ramps and 11 off-ram
- 6-hour simulation, 5 AM to 11 AM
- Ramp metering activates from 6 AM to 9:30 AM
- Demand: collected from field data
- 100 % human-driven vehicles
- External behavior model:
  - Reaction time: 0.8 s
  - Mean headway: 1.4 m
  - Maximum acceleration: 2.0 m/s2
  - Maximum deceleration: -4.0 m/s2
  - Lane-changing desire threshold: 0.15



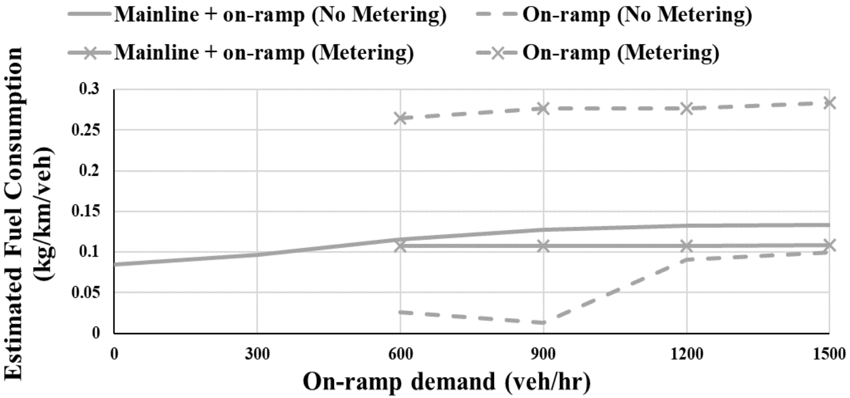
APPROACH

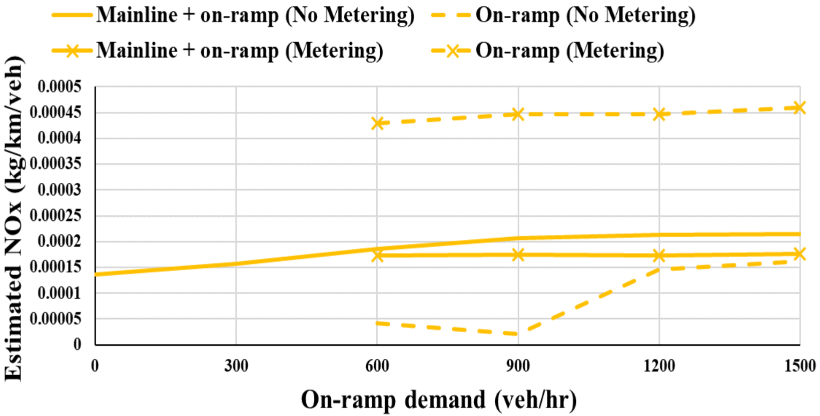
Control strategies

- **Local responsive ramp metering (LRRM)**
  - The LRRM algorithm determines RM rate based on nearby freeway conditions. The RM rate for each on-ramp is isolated with each other. We implemented this algorithm according to the LRRM look-up table in District 3, California.
- **Coordinated ramp metering (CRM)**
  - The CRM algorithm determines RM rate by looking at mainline occupancy/flow of the whole corridor, the demand at all onramps and the out-flow from off-ramps. It uses a simplified version of Optimal Control, called Model Predictive Control (MPC) based on a linear cell transmission model with on-ramp queue dynamic model.
- **Variable speed advisory (VSA)**
  - VSA is intended to create a discharging section upstream of the bottleneck and to regulate its flow such that the bottleneck's feeding flow is closer to its capacity flow. The VSA algorithm is determined by mainline flow, on-ramp demand and length limit (storage capacity), and limits on speed variation over time and space for driver acceptance and safety.

ACCOMPLISHMENTS

Performance of isolated bottleneck

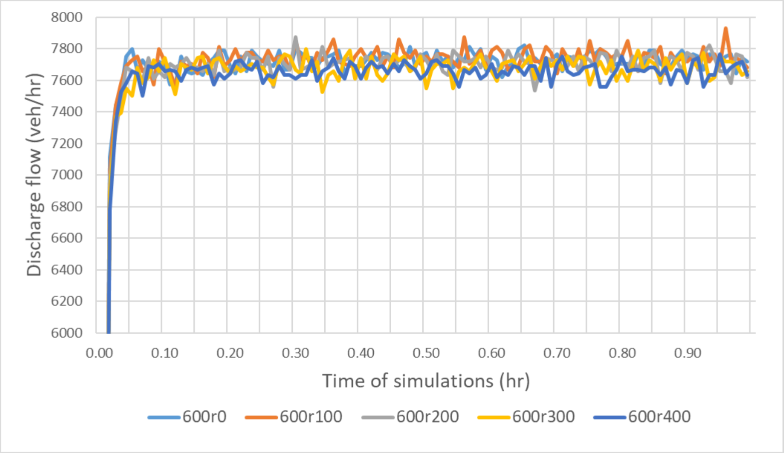


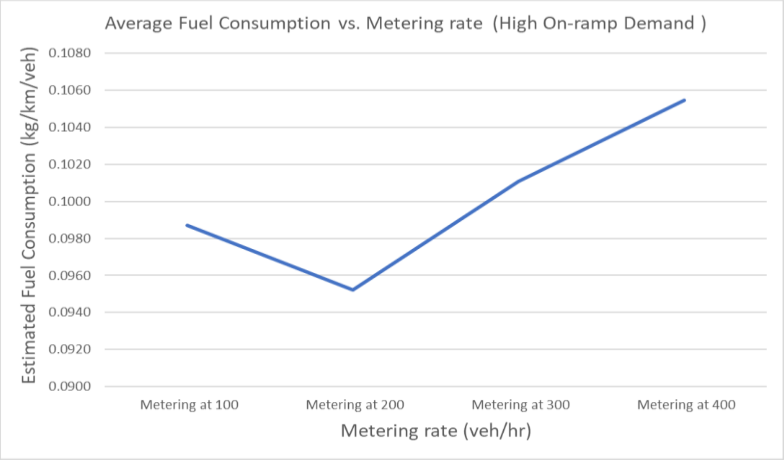


- Different types of emissions and fuel consumptions share a very similar pattern over different scenarios;
- The overall emission/fuel consumption per vehicle increases over 50% as the on-ramp demand increase from 0 to 1,500 veh/hr, which is caused by more yielding and merging behaviors;
- Then it decreases about 20% after the activation of ramp metering with high on-ramp demand (>900 veh/hr);
- The results are consistent with capacity drop phenomenon (starts from 400 veh/hr and reaches its peak after 900 veh/);
- Emissions at on-ramp get much worse, while the whole network benefit a lot.

ACCOMPLISHMENTS

Performance of isolated bottleneck

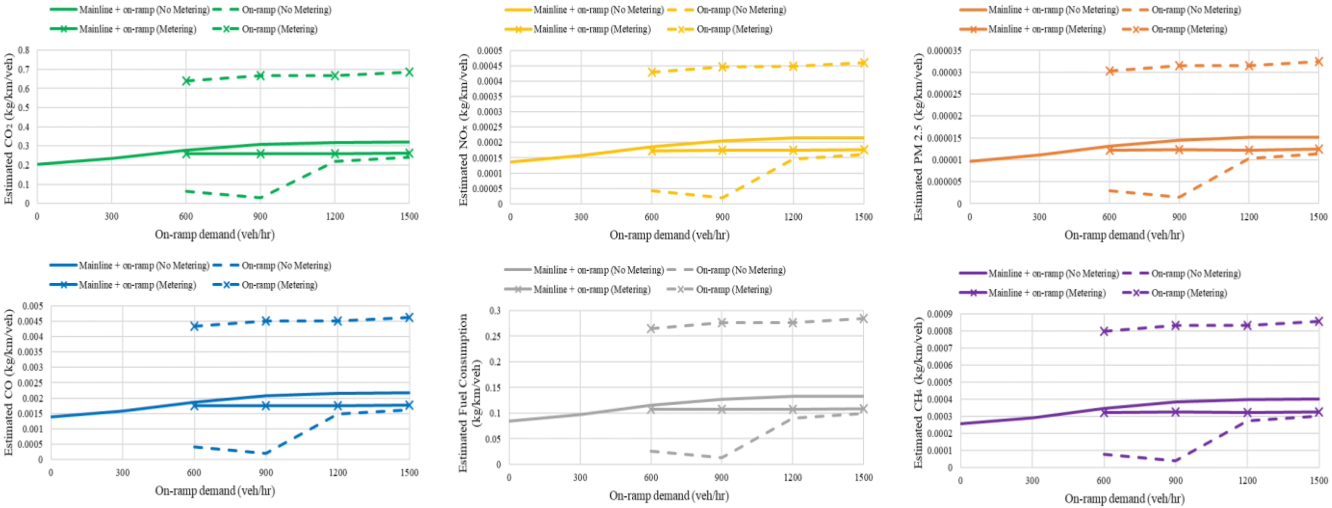




Discharge flow under 600 veh/hr on-ramp demand, with metering rate from 0 to 400 veh/hr.

- Metered at 0 - 400 veh/hr will keep the mainline throughput at its maximum level;
- Metered at 200 veh/hr can achieve highest fuel efficiency, adding another 5% emission and fuel consumption reduction, compared to 400 veh/hr metering rate;
- Metered at 400 veh/hr could give least penalty to on-ramp vehicles.

Appendix



On-ramp Demand	No Metering	Metered at 0	Metered at 100	Metered at 200	Metered at 300	Metered at 400
0	0.0848	/	/	/	/	/
300	0.0968	/	/	/	/	/
600	0.1141	0.0889	0.0951	0.0950	0.1014	0.1049
900	0.1264	0.0887	0.1083	0.0952	0.1008	0.1055
1200	0.1317	0.0889	0.0963	0.0953	0.1012	0.1057
1500	0.1322	0.0900	0.0951	0.0953	0.1010	0.1057